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Pressure Transient Analysis of Multi-stage Hydraulically Fractured Horizontal Wells

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Abstract

The horizontal well with multiple transverse fractures has proven to be an effective way to exploit tight reservoirs economically. Due to the nature of ultralow permeability, it would take a significant long period of time for a well producing in transient flow regimes. Therefore, pressure transient analysis for such a well is important in both evaluation of fracturing treatment by estimating fracture and reservoir parameters and prediction of the long-term production behavior of wells in oil recovery. This paper discusses the analysis of pressure-transient responses of horizontal wells intercepting multiple infinite-conductivity transverse fractures. Then a numerical model is utilized to simulate the whole well flow regimes and pressure transient characteristics of multiple fractured horizontal wells. Accordingly, appropriate analytical pressure-transient models and analysis procedures are provided to determine fracture properties, i.e. average fracture half-length and spacing and estimate the oil in place in the stimulated reservoir volume.

Keywords

Pressure Transient; Multiple Fractured Horizontal Wells; Analytical Models; Stimulated Reservoir Volume

Introduction

Currently, economic extraction of hydrocarbon from tight formations is featured by completion of a long horizontal lateral intersected with multiple transverse fractures (Yost, A.B. and Overbey, W.K., 1989). Pressure transient characteristics and analysis of fractured horizontal wells have been discussed in several studies. Larsen and Hegre (1991 and 1994) studied pressure transient behavior of a horizontal well with transverse fractures and provided description of pressure-transient flow regimes with corresponding analytical solutions. Al-Kobashi et al (2006) concentrated on the pressure-transient characteristics at the early-time flow regimes. They described the fracture storage induced flow regimes for the multiple transverse fractured horizontal wells (MTFHW) including fracture-radial, radial-linear flow and bilinear linear flow. In their literatures, the early time corresponding to the period prior to the start of the interference between fractures was considered. Since the fracture interference is negligible, the pressure response of the MTFHW was correlated with the single fracture responses. Zerzar et al (2004), Clarkson et al (2009) and Freeman et al (2009) concentrated on the pressure-transient characteristics at relatively later times (after the end of fracture-storage), and described flow regimes for the MTFHW including pseudo-linear flow, pseudo-radial and compound linear flow(or bi-radial flow) before infinite-acting, pseudosteady state or steady state flow related to the extent of the well drainage area. Song et al (2011) introduced the term pseudo pseudosteady state for the flow regime between pseudolinear flow and compound linear flow.

Because the matrix permeability of tight formations is extremely low, like shale typically in a range of tens to hundreds of nano-darcy, the permeability of hydraulic fractures with milli-darcy scale dominates the transient flow. And then the fracture interference dominated flow regimes take more time in consequence. In this paper, we concentrated on the pressure transient response at the fracture interference dominated flow regimes. In order to ensure the coherence, we studied the entire pressure transient behavior of the MTFHW in tight formations and provided description of pressure-transient flow regimes with corresponding analytical solutions. Numerical synthetic cases have proved our analytical models and analysis procedures.

Pressure Transient Mathematical Model

We consider the flow of a slightly compressible liquid in a bounded reservoir that is in the form of a rectangle. The porous medium is assumed to be homogeneous system and may exhibit simple

anisotropy. Each fracture that intercepts the horizontal wells has same properties, i.e. length, width, permeability and porosity are identical. All fractures produce against a wellbore pressure that may be a function of time under the constant-rate. Such a model can be used to analyze the production or test data from multiple fractured horizontal wells.

For the mathematical model considered here, in the absence of wellbore storage effects, four major flow periods to control the well pressure response are expected provided that the fracture-storage induced flow period is non-exist: (1) an early-time flow period wherein the system behaves as if it were an n-layer, commingled reservoir where n is the total number of fractures, (2) an intermediate-time flow period that reflects interference effects between fractures, (3) a late-time flow period during which the composite fracture system behaves as if it were a single fracture equal to the spacing between the outermost fractures, and (4) finally reservoir boundary dominated flow period.

MTFHW Flow Regimes

To set the stage for our discussion on the analysis of pressure-transient responses, here a summary of the flow regimes of multiple fractured horizontal wells is presented (sketched in Fig. 1). Each of the regimes shown in Fig. 1 is discussed below.

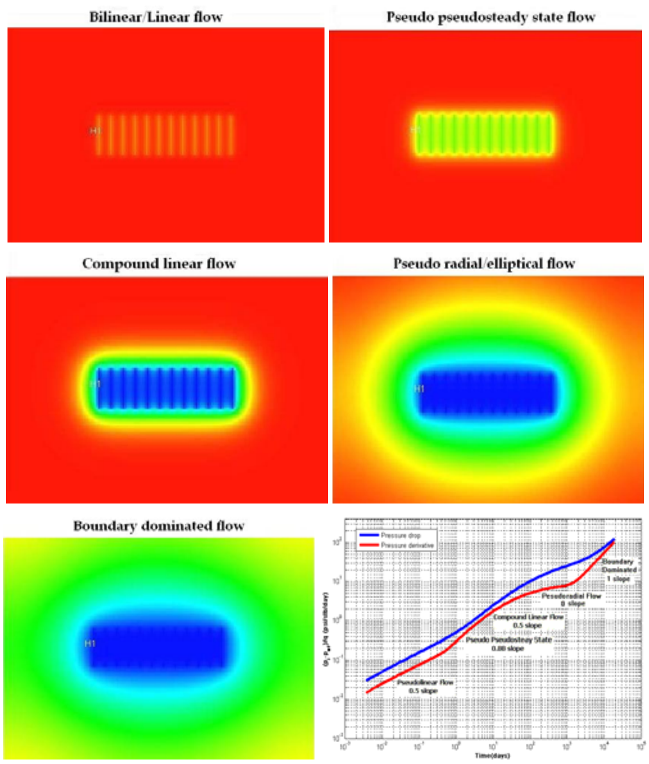

FIG. 1 SCHEMATIC OF MTFHW FLOW REGIMES (SIMULATION WITH ECLIPSE)

Early-time Linear or Bi-linear Flow

In this flow period, fluid flows down the fracture and flow in the reservoir is normal to the fracture planes. The type of flow regime (linear or bilinear) that dominates this period will depend on the fracture conductivity and length. Flow across the fracture tips is negligible and each fracture behaves independently of the other fracture.

Pseudo-Pseudosteady State Flow

During this flow regime, pressure interference between fractures dominates while the flow across the boundary between the inner and the outer stimulated reservoir volume(SRV) starts but insignificant. It is an approximate pseudo-steady state flow, with which the inner SRV is depleted with limited contribution from the outer SRV.

Compound Linear flow

During this regime, fracture interacts. The system behaves as if flow takes place to a fractured well that is parallel to the azimuth of the horizontal well. The flow pattern is predominantly normal to the vertical plane that contains the horizontal well.

Pseudoradial Flow

In this period, flow across the tips of the horizontal well becomes dominant and the flow pattern is similar to that of the long-term behaviour of vertically fractured wells.

Boundary Dominated Flow

This flow period occurs when the reservoir boundary is reached. In the case of closed boundaries, the flow will eventually reach pseudo-steady state.

The flow regimes presented above may not exist in a single test. Depending on the specific properties of the fracture and reservoir, some of the flow regimes may be absent. For the moderate ratios of fracture length and spacing, the pseudo-pseudosteady state flow regime may be nonexistent or replaced by a transitional period, such as bi-radial flow regime. It is possible that the pseudoradial flow regime may not exist because of well interference or boundary effects. Methods to analyze pressure data are presented below.

Straight-Line Analysis of Pressure-Transient Responses

For the mathematical model and flow regimes discussed above, straight-line analysis techniques can

be used for the estimation of the fracture properties and the oil in place in the stimulated reservoir volume. In this section, pressure transient equations dominating each flow regime will be presented. And then we will demonstrate the use of the straight-line analysis for the pressure responses of multiple fractured horizontal wells.

Early-time Linear Flow

The pressure response during the early-time linear flow period is given by

$$\Delta p_{wf} = 4.0641\frac{qB}{nhx_f}\sqrt{\frac{\mu t}{k\varphi c_t}} + \frac{141.2qB\mu}{kh}\left[s + s_p\right] \qquad (1)$$

where s is the fracture surface skin and s_p is a pseudoskin factor that accounts for the additional pressure drop due to finite conductivity, flow choking, and fracture geometry. The early-time fracture linear flow period is characterized by a ½ slope straight line on a log-log plot of the derivative responses.

Based on Eq.1, a plot of pressure drop versus square root of time yields a straight line with a slope of

$$m_{fl} = 4.0641\frac{qB}{nhx_f}\sqrt{\frac{\mu}{k\varphi c_t}} \qquad (2)$$

and as in the case of multiple fractured horizontal wells, the fracture half-length x_f can be obtained from Eq.2 if the formation height and reservoir permeability are known. The time at the end of early-time linear flow occurs when flow to adjacent fractures interferes. The time of this occurrence is given by

$$t_e = \frac{x_s^2\varphi\mu c_t}{4*(0.029)^2 k} \qquad (3)$$

where x_s is the fracture spacing in ft.

Pseudo Pseudo-Steady State Flow

As indicated before, the pressure behaviour during the pseudo pseudo-steady state flow period is similar to the pseudo-steady state flow, with which the inner fracture is depleted with limited contribution from the outer fracture. The pressure drop during this flow regime is given by

$$\Delta p_{wf} = \frac{qBt}{24V_p c_t} + \Delta p_{\text{int}} \qquad (4)$$

where Δp_{int} is the longitudinal intercept when plotting pressure drop versus time and yields a straight line with a slope of

$$m_{qf} = \frac{qB}{24V_p c_t} \qquad (5)$$

Thus, the SRV pore volume V_p can be obtained from Eq. 5.

Pseudoradial Flow

The dimensionless pressure behavior during the intermediate-time pseudoradial flow period is similar to the line-source solution in a homogeneous reservoir with an additional pressure drop because of the effect of transverse fractures. The pressure drop during this flow regime is given by

$$\Delta p_{wf} = \frac{162.6qB\mu}{kh}\left[\log\left(\frac{2.64\times10^{-4}kt}{\varphi\mu c_t r_w'^2}\right) + \frac{s+s_p}{1.1516} + 0.3513\right] \qquad (6)$$

Based on Eq. 6, the slope of the semi-log straight line during pseudoradial flow is given by

$$m_{pl} = \frac{162.6qB\mu}{kh} \qquad (7)$$

Thus, the formation permeability k can be calculated directly from Eq. 7.

Pseudo-Steady State Flow

The pressure drop during the pseudo-steady state flow regime is given by

$$\Delta p_{wf} = \frac{qBt}{24V_r c_t} + \Delta p_{\text{int}}^* \qquad (8)$$

where Δp_{int}^* is the longitudinal intercept when plotting pressure drop versus time and yields a straight line with a slope of

$$m_{ql} = \frac{qB}{24V_r c_t} \qquad (9)$$

Thus, the reservoir pore volume V_r can be obtained from Eq. 9.

Straight-Line Analysis Example

We now use a synthetic example to demonstrate the straight-line analysis of pressure transient responses of the MTFHW. The synthetic dataset used in the study is generated by a numerical model, considering a horizontal well intersected by multiple transverse fractures with identical properties. The modeled fractures are considered to be rectangular, vertical and transversal relative to well direction. Infinite conductivities are considered in this study. The wellbore hydraulics is honored by a multi-segmented wellbore model. The reservoir simulation cells are connected to the wellbore model using conventional techniques. Skin at each interface between reservoir cells and the wellbore model is assumed to be zero. The model considers the production of single-phase oil from an isotropic formation. The hydraulic fracture is modeled with Local Grid Refinement (LGR) technique. A series of thin blocks within LGR is assigned with the

properties of hydraulic fractures.

To test this particular grid model, a horizontal well model with 12 hydraulic fractures 60 ft equally spaced has been constructed. This allows the early time pressure transient behavior to be captured. Bottomhole pressure is simulated for 1000 days of production while a constant rate is specified in the model. A small rate is required to drain the tight formation with physically feasible bottomhole pressures. Basic reservoir and well data are listed in Table 1.

TABLE 1 PROPERTIES OF RESERVOIR, FLUID AND FRACTURE FOR THE EXAMPLE

Initial reservoir pressure	2550 psia
Total compressibility	3e^{-4} pis-1
Matrix porosity	0.0455
Matrix permeability	3e^{-3} md
Initial oil density	62.47 lb/ft3
Initial oil viscosity	1.25 cp
Formation thickness	30 ft
Fracture half-length	100 ft

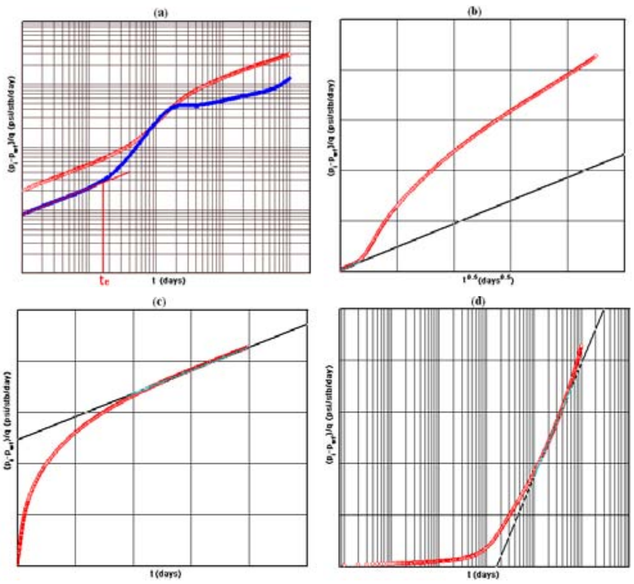

FIG. 2 STRAIGHT-LINE ANALYSIS PLOTS OF THE SIMULATED DATA IN THE EXAMPLE

Fig. 2(a) shows a log-log diagnostic plot of the data to be analyzed in this example. It can be seen from Fig. 2 that the early-time linear flow period (0.5-slope on derivative responses) is followed by the pesudo pesudo-steady state flow (0.88-slope on derivative responses) and an almost pseudoradial flow (0-slope on derivative responses). At late time, the pressure derivative goes upwards which reflects the reservoir boundary effect.

A plot of $\Delta p / q$ vs. the square-root-of-time during the early-time linear flow period, shown in Fig. 2(b), yields a straight line with slope m_{fl}. Using Eq. 2 with the data in Table 1, the fracture half-length x_f is calculated to be 107.16 ft. With the end point of linear flow, $t_e = 2$ days on log-log plot in Fig. 2(a), using Eq. 3 and the data in Table 1, the fracture spacing x_s can be calculated as 59.57 ft.

A Cartesian plot of $\Delta p / q$ vs. time during the pesudo pesudo-steady state of the fracture system shown in Fig. 2(c), yields a straight line with slope m_{qf}. Using Eq. 5 with the data in Table 1, the stimulated reservoir volume is calculated to be 6.3*10^6 ft^3.

Note from Fig. 2(a) that the pseudoradial flow behavior is evident from the flat derivative responses before reaching the reservoir boundary. Thus, the plot of $\Delta p / q$ vs. the logarithm of time, shown in Fig. 2(d), yields a straight line with a slope of m_{pl}. Using this slope and Eq. 7 with the data given in Table 1, the formation permeability k, is calculated to be 0.0036 md.

Conclusions

In this paper, we have studied the pressure transient behavior of multiple infinite-conductivity transverse fractures intercepted by a horizontal well. Five basic flow regimes of a MTFHW have been identified and equations have been provided for specialized analysis of pressure and pressure derivative plot. A calculation procedure has been presented with a numerical synthetic case, which demonstrated that the early-time linear flow before the occurrence of fracture interference and the fracture interference dominated pseudo pseudo-steady state flow regimes are key to the analysis due to estimates for the fracture properties and the oil in place in the SRV heavily depending on these two flow regimes.

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REFERENCES

Al-Kobaisi, M. "Pressure-Transient Response of a Finite-Conductivity Fracture Intercepted by a Horizontal Well." MSc Thesis, Colorado School of Mines, Golden, CO 2005.

Al-Kobaisi, M., Ozkan, E., Kasogi, H., and Ramirez, B. "Pressure-Transient Analysis of Horizontal Wells with

Transverse, Finite-conductivity Fractures." Paper PETSOC 2006-126 presented at the Petroleum Society's 7th Canadian International Petroleum Conference (57th Annual Technical Meeting), Calgary, Alberta, Canada, 13-15 June, 2006.

A. Zerzar, D.Tiab and Y.Bettam "Interpretation of Multiple Hydraulically Fractured Horizontal Wells." SPE 88707, presented at the 11th Abu Dhabi International Petroleum Exhibition and Conference, Abu Dhabi, U.A.E., 10-13 October, 2004.

Clarkson, C.R., Jordan, C.L., Ilk, D., and Blasingame, T.A. "Production Data Analysis of Fractured and Horizontal CMB Wells." Paper SPE 125929 presented at the 2009 SPE Eastern Regional Meeting, Charleston, West Virginia, 23-25 September, 2009.

Larsen, L. and Hegre, T.M. "Pressure-Transient Behavior of Horizontal Wells with Finite-Conductivity Fractures." SPE 22076, presented at the SPE International Arctic Conference, Anchorage, AK, May 29-31, 1991.

Larsen, L. and Hegre, T.M. "Pressure Transient Analysis of Multifractured Horizontal Wells." SPE 28389, presented at the SPE Annual Technical Conference and Exhibition, New Orleans, LA, Sept. 25-28, 1994.

Ozkan, E, Brown, M., Raghavan, R., and Kazemi, H. "Comparison of Fractured Horizontal-Well Performance in Conventional and Unconventional Reservoirs."Paper SPE 121290 presented at the SPE Western Regional Meeting, San Jose, California, 24-26 March, 2009.

Raghavan, R.S., Chen, C. and Agarwal, B."An Analysis of Horizontal Wells Intercepted by Multiple Fractures."SPE Journal 2 (3):235-245. SPE-27652-PA, 1997.

Song, B., Economides, M.J., and Ehlig-Economides, C.A. "Design of Multiple Transverse Fracture Horizontal Wells in Shale Gas Reservoirs." Paper SPE 140555 presented at the 2011 SPE Hydraulic Fracturing Technology Conference, Woodlands, TX, 24-26 January, 2009.

Yost, A.B. and Overbey, W.K. "Production and Stimulation Analysis of Multiple Hydraulic Fracturing of a 2,000 ft Horizontal Well." SPE 19090, presented at the SPE Gas Technology Symposium, Dallas, TX, June 1989.

Nomenclature

B = formation volume factor, rb/stb

r_w = well radius, ft

c_t = total compressibility, 1 /psia

h = formation thickness, ft

k = formation permeability, md

s = fracture skin factor, dimensionless

s_p = pseudoskin factor, dimensionless

x_s = fracture spacing, ft

x_f = fracture half-length, ft

Δp_{wf} = drawdown pressure drop, psia/day

q = flow rate, stb/day

t = time, hours

t_e = end of early-time linear flow, hours

n = fracture number, dimensionless

ϕ = porosity, fraction

μ = viscosity, cp

V_p = SRV pore volume, ft^3

V_r = Reservoir pore volume, ft^3